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On the maximum wind in tropical cyclones

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Summary

The maximum wind, central pressure and radius of maximum wind in cyclonic storms and typhoons of the western North Pacific in the year 1978 as observed by US reconnaissance aircraft are analysed by regression and correlation techniques and an equation relating the three parameters is derived.

Introduction

The maximum wind in tropical cyclones is of great importance and interest to the meteorologist. Takahasi (1948) attempted to obtain an expression for the maximum surface wind in terms of the central pressure depth using the pressure profile equation

$$p = p_0 - \{c/(r + r_0)\} \qquad \text{(1)}$$

given by Horiguti (1926). In the above equation, p is pressure, r is radial distance; p_0, r_0, and c are constants. Takahasi used the peripheral pressure for p_0 and the radial distance of 'half pressure depth' as r_0, and from the cyclostrophic wind relationship he obtained

$$v_m^2 = (p_0 - p_1)/4\rho \qquad \text{(2a)}$$

where, v_m is the maximum wind, p_1 is the central pressure and ρ is the density of the air. If v_m is expressed in knots and p_0 and p_1 in millibars, and ρ is taken as $1{\cdot}29 \times 10^{-3}$ g cm^{-3}, equation (2a) would reduce to

$$v_m = 8{\cdot}8(p_0 - p_1)^{\frac{1}{2}} \qquad \text{(2b)}$$

He himself felt that the above equation may give underestimates and suggested a value of 11·7 for the coefficient on the basis of direct, though meagre, wind observations. Further, it can be shown that the radius of maximum wind, r_m, is equal to r_0 in the above model. But experience shows that r_m is much smaller than r_0.

The Hydrometeorological Section of the US Weather Bureau (1954) had been using the equation

$$(p - p_1)/(p_n - p_1) = e^{r/r_m} \qquad \text{(3)}$$

for the pressure profile in tropical cyclones, where e is the base of natural logarithms and p_n is the peripheral pressure. Using this equation and the cyclostrophic wind relationship, Myers (1957) showed that

$$v_m^2 = (p_n - p_i)/e\rho \quad .. \quad .. \quad .. \quad .. \quad .. \qquad (4a)$$

This equation is equivalent to

$$v_m = 10{\cdot}68(p_n - p_i)^{\frac{1}{2}} \quad .. \quad .. \quad .. \quad .. \qquad (4b)$$

when the wind is expressed in knots and the pressure in millibars.

Fletcher (1955) obtained the following empirical equation for the maximum wind

$$v_m = 16(p_n - p_i)^{\frac{1}{2}} \quad .. \quad .. \quad .. \quad .. \quad .. \qquad (5)$$

This equation was reported to be giving high values for v_m (Dunn and Miller 1960).

Subbaramayya and Fujiwhara (1979) used the reconnaissance aircraft data obtained by the US Air Force in typhoons of the western North Pacific and obtained the following empirical relationships:

$$v_m = 12{\cdot}4(1010 - p_i)^{\frac{1}{2}} - 8{\cdot}8 \quad .. \quad .. \quad .. \quad .. \qquad (6a)$$

and

$$v_m = (1010 - p_i) + 25 \quad .. \quad .. \quad .. \quad .. \quad .. \qquad (6b)$$

The standard deviations of the errors of estimation for the two equations were practically the same and hence they laid stress on the usefulness of the latter equation in operational analysis because of its simplicity, but it was not clear what 'power law' relates maximum wind and central pressure depth. In fact, Shea and Gray (1973) indicated a relationship, graphically, which shows a power greater than unity for $(1010 - p_i)$.

Theoretical considerations

According to the generally accepted model of a tropical cyclone, air converges from the surroundings in the lower levels to the centre of the cyclone where it ascends and diverges outward at higher levels. The air-parcels at low levels gain kinetic energy while running down the pressure gradient and hence the maximum wind can approximately be written as

$$v_m^2 = (2/\rho)(p_n - p_i) \quad .. \quad .. \quad .. \quad .. \quad .. \qquad (7a)$$

or

$$v_m = 24{\cdot}9(p_n - p_i)^{\frac{1}{2}} \quad .. \quad .. \quad .. \quad .. \quad .. \qquad (7b)$$

where v_m, p_n and p_i are expressed in the same units as in the earlier equations. The coefficient on the right-hand side is quite large compared to those obtained in the empirical investigations. This is because, in the above calculations, loss of energy due to frictional forces was not taken into account.

Riehl (1963) took the frictional force into consideration and, assuming the conservation of potential vorticity to hold good, showed that in a steady state hurricane

$$v_\theta^2 r = K \quad .. \quad .. \quad .. \quad .. \quad .. \quad .. \qquad (8)$$

in the low-level inflow layer, where v_θ is the tangential velocity and K is constant. Further, assuming the cyclostrophic wind relationship to hold good as a first approximation, we may write

$$K/r^2 = (1/\rho)(\partial p/\partial r)$$

Integrating the above equation from the periphery to the point of maximum wind and substituting the central pressure value for the pressure at the radius of maximum wind, which is reasonable because the maximum winds are observed practically near the eye-wall, we get

$$K(r_n - r_m)/r_n r_m = (p_n - p_l)/\rho$$

Since r_m is very small compared to r_n, the radius of the cyclone,

$$K/r_m \approx (p_n - p_l)/\rho$$

and

$$v_{\theta,m}^2 \approx (p_n - p_l)/\rho \quad \ldots \quad (9a)$$

Hence,

$$v_{\theta,m} \approx 17{\cdot}6(p_n - p_l)^{\frac{1}{2}} \quad \ldots \quad (9b)$$

It is easy to see that the above equation over-estimates $v_{\theta,m}$ because of the assumption of the cyclostrophic wind relationship over the entire area of the cyclone and the other approximations made in deriving the relationship.

Further, Riehl (1963) in his model showed that

$$v_{\theta,m} = fr_o^2/2r_m \quad \ldots \quad (10)$$

where r_o is the radius at which the cyclonic flow changes to anticyclonic in the upper outward layer and f is the Coriolis parameter. Equation (10) shows that $v_{\theta,m}$ and r_m are inversely related and for the same r_o and r_m values, $v_{\theta,m}$ should be more at higher latitudes because the Coriolis parameter is in the numerator.

The authors in this paper have attempted to study the nature of the functional relationship between maximum wind and the central pressure depth and the dependence of the maximum wind on the radius of maximum wind and the latitude.

Data

Central pressure, maximum wind and location of maximum wind in cyclonic disturbances and typhoons in the north-west Pacific are being observed through US reconnaissance aircraft flights.

The observations are disseminated by the Joint Typhoon Warning Center, Guam, for the use of the littoral and island countries in the area. These observations are available in the data archives at the Japan Meteorological Agency, Tokyo, for quite a considerable period. However, observations of the radius of maximum wind are available since 1978 only. The authors have therefore used data on the typhoons for the year 1978 in the present study.

There were 28 cyclonic storms of different intensities in the western North Pacific during the period June to November 1978. Some of them became major typhoons. There were about 130 reconnaissance reports with simultaneous observations of all the parameters necessary for the present study. The lowest pressure report in the sample of observations is 878 mb and the maximum wind is 150 kn. Only cases with maximum wind greater than 30 kn have been considered for the study.

Analysis and results

The peripheral pressure in all the cases was assumed to be 1010 mb in determining the central pressure depth. Logarithmic regressions between v_m, $(1010 - p_l)$, r_m and $\sin\theta$, where θ is the inflow angle, with $\lg v_m$ as the dependent variable were first obtained. The regression coefficients so obtained are given in Table I. Using these regression coefficients as the exponent values of the different independent variables, their total correlations with v_m as well as the partial correlations were then calculated and are presented in Table II.

Table I. *Regression coefficients*

	$\lg(1010 - p_1)$	$\lg r_m$	$\lg \sin\theta$
$\lg v_m$	0·591	−0·319	−0·412

Table II. *Correlation coefficients*

	$(1010 - p_1)^{0.591}$	$r_m^{-0.319}$	$(\sin\theta)^{-0.412}$
Total correlation	0·856	0·671	0·361
Partial correlation	0·805	0·512	0·193

It can be seen that the total and partial correlations of maximum wind with central pressure depth and the radius of maximum wind are quite significant while those with sin θ are low. The corresponding simple and multiple regression equations for v_m involving $(1010 - p_1)$ and r_m are

$$v_m = 8{\cdot}3(1010 - p_1)^{0.591} - 3{\cdot}358 \quad \ldots \quad (11)$$

and

$$v_m = 6{\cdot}7(1010 - p_1)^{0.591} + 87{\cdot}7 r_m^{-0.319} - 24 \quad \ldots \quad (12)$$

The coefficients of determination (i.e. squares of the correlation coefficient) of the two equations are 0·73 and 0·81 respectively.

The best possible exponent values for $(1010 - p_1)$ and r_m, when they are used in the product form, also were determined, and the corresponding regression equation for v_m is

$$v_m = \frac{20{\cdot}6(1010 - p_1)^{0.472}}{r_m^{0.168}} - 2{\cdot}13 \quad \ldots \quad (13)$$

The coefficient of determination of this equation is found to be 0·812.

Similar analysis was done with v_m^2 as the dependent variable. The regression coefficients and the correlation coefficients so obtained are presented in Tables III and IV.

Table III. *Regression coefficients*

	$\lg(1010 - p_1)$	$\lg r_m$	$\lg \sin\theta$
$\lg v_m^2$	1·182	−0·638	−0·824

Table IV. *Correlation coefficients*

	$(1010 - p_1)^{1.182}$	$r_m^{-0.638}$	$(\sin\theta)^{-0.824}$
Total correlation	0·8799	0·6614	0·4245
Partial correlation	0·8365	0·5068	0·1921

The regression coefficients are approximately twice as large as those in Table I but in this case the correlations with $(1010 - p_1)$ are slightly better than in the earlier case. The simple and multiple regression equations for v_m^2 involving $(1010 - p_1)$ and r_m are

$$v_m^2 = 65{\cdot}5(1010 - p_1)^{1.182} - 57{\cdot}4 \quad \ldots \quad (14)$$

$$v_m^2 = 54{\cdot}5(1010 - p_1)^{1.182} + 15\,348 r_m^{-0.638} - 1631 \quad \ldots \quad (15)$$

The coefficients of determination of these equations are 0·77 and 0·84. These values are higher than the corresponding values of equations (11) and (12).

The best regression equation for v_m^2 with $(1010 - p_1)$ and r_m in the product form is obtained as

$$v_m^2 = \frac{400(1010 - p_1)^{0.943}}{r_m^{0.336}} + 65 \quad \ldots \quad (16)$$

and the coefficient of determination of this equation is 0·85. This is again not only higher than that of the corresponding regression equation for v_m (13), but also greater than those of equations (14) and (15). Therefore, equation (16) can be considered as the best regression equation. However, it may be noted that the exponent values of $(1010 - p_1)$ and r_m in this equation are nearly equal to 1 and $-1/3$ respectively. The authors, hence, assumed these simple power values and evaluated another regression equation for v_m^2 by keeping the peripheral pressure as an unknown constant. The resulting regression equation is

$$v_m^2 = 302(1012{\cdot}6 - p_1)/r_m^{1/3} \quad \ldots \quad (17)$$

The coefficient of determination of this regression equation is 0·85 and is surprisingly greater than that of equation (16). The authors, therefore, suggest that equation (17) can be used to give best possible estimates of maximum wind in typhoons from the central pressure and the radius of maximum wind. A similar attempt, with the central pressure alone as the independent variable, gave the regression equation

$$v_m^2 = 161(1003 - p_1) \quad \ldots \quad (18)$$

whose coefficient of determination is 0·78.

The values for the peripheral pressure obtained in the above two regressions are quite different. The value in the former equation is close to the actual and it therefore suggests that r_m is also an important factor in the estimation of the maximum winds as well as the central pressure depth.

The work relates only to tropical cyclones in the western North Pacific and those in other parts of the world may differ somewhat in their characteristics (see for example Gray 1979), and therefore caution is required in applying the equation in other areas.

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Rain-gauge network rationalization and its advantages

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Summary

The purpose and methods of rain-gauge network rationalization are described and the ways in which users of rainfall data can benefit from improved rain-gauge network design are discussed; the rationalization of the networks in the Wessex Water Authority area is used as an example.

Introduction

The Meteorological Office provides archiving and validation facilities for daily, weekly and monthly data and, in conjunction with Water Authorities, inspects rainfall stations to ensure a continuing high standard of siting and observational practice. However, although there is no national standard system for archiving automatically recorded data in machinable form, hourly totals from an increasing number of stations are being archived by the Meteorological Office and some quality control is applied.

The costs of operating these networks and of collecting, processing and disseminating the data have increased in recent years (the purchase price of a standard rain-gauge is now about £80) and it is necessary to consider whether the data requirements of users could be met in a more cost-effective manner. This is the main purpose of the Rain-gauge Network Rationalization Project, described by O'Connell *et al.* (1977, 1978, 1979) and Jones *et al.* (1979) in which objectively based methods of network design have been evolved and tested in a case-study. For this evolutionary process the main stages were:

(a) a determination, in numerical terms, of the users' requirements for data,

(b) evaluation of the existing networks in the case-study area, using (1) network operation considerations and (2) statistical methods, and

(c) redesign of the networks, where necessary, to satisfy the users' requirements more effectively.

The reasons why an objectively based rationalization exercise might be expected to be superior to a purely subjective approach based on experience will be discussed, and each of the stages of the rationalization process will be described, with particular reference to the rationalization exercise carried out in the Wessex Water Authority area (O'Connell *et al.* 1978). Additionally, it will be shown how the Water Authority, the Meteorological Office and the other users of rainfall data may benefit (in a qualitative sense) from network rationalization.

Network design considerations

More than one approach to network design is possible. A subjective approach can be adopted in which the new network is evolved from an existing network by consideration of various practical factors and empirical criteria, such as the desired inter-gauge spacing; alternatively, an objectively based method involving statistical analysis of the rainfall field defined by the network may be coupled with elements of the simpler pragmatic approach.

Before adopting either approach it is necessary to consider the factors which influence the ability of a network to provide an adequate representation of the rainfall in time and space. These include:

(a) the type of rainfall,
(b) the density and configuration of the gauge network,
(c) the time resolution of the measuring equipment,
(d) the observational procedures used, and
(e) the accuracy of individual point measurements of rainfall.

The question of how best theoretically to distribute gauges within an area is a *network design* problem, but whether or not the gauges provide reliable measurements of point rainfall is a problem of *network operation*. Because of the interaction of the five factors, a complete approach to the redesign of an existing network will require both the use of statistical techniques for identifying the optimal configuration of gauges and practical consideration of the quality and reliability of the observations.

Using a subjective approach, an apparently satisfactory network can be evolved, but the complexity and interaction of the above factors will preclude any scientific evaluation of the adequacy of such a network, and quantitative comparison with users' requirements is not possible. However, using the objective methods described by O'Connell *et al.* (1978), it is possible to compare the accuracy of estimation at points in the rainfall field between gauges at any stage of the evolution of the design network with that required by users. Another advantage of the objectively based technique is that it is repeatable and is thus not dependent on individual preferences. The same methods should be applicable in different areas, resulting in a uniform standard of network design. Additionally, the assessment of potential networks can be carried out swiftly by computer.

An important fact demonstrated later is that even in areas of apparently uniform topography, a uniform inter-gauge spacing does not necessarily achieve a consistent level of accuracy across the area. The identification of the areas where denser networks are required and the estimation of the numbers of gauges needed in these areas are difficult problems to solve, except by objective techniques.

The stages of a network rationalization exercise

(a) *Evaluation of the users' requirements for rainfall data*

The principal users of rainfall data are the regional Water Authorities, the Ministry of Agriculture, Fisheries and Food (MAFF) and the Meteorological Office, which through its hydrometeorological enquiries section provides data to a variety of commercial and other users, including insurance companies, research organizations and engineers. Table I lists the major uses of rainfall data, the types of data required (usually daily, or shorter period totals), and whether these are required in 'real time'.

In the rationalization exercise, it is necessary to quantify the accuracies required by the users of rainfall data, at points or over areas, so that the accuracy of estimation which can be achieved by interpolating from the existing or proposed gauges can be compared with these requirements. This, too, is not an easy task as many users have never quantified the accuracy required for their activities. However, since most users accept that the present networks are accurate enough for their purposes, the accuracy of estimation which can be achieved using the existing network can form the reference point for a redesigned network. Ideally, rationalized networks should provide at least the same average estimation accuracy as existing networks.

Special network requirements need to be defined so that the redesigned networks can incorporate as many of these as is practicable. For example, some users require a uniform background network of gauges, some require long records, whilst others need denser networks in particular areas. Although it may not be explicitly stated, the requirement for the data to be of a uniformly high standard implies

Table I. *Some uses of rainfall data in the United Kingdom, with types of network required.*

User	Purpose	Network required: Gauges read daily	Recording gauges	Gauges transmitting data in real time
Water Authority	Design of flood alleviation works	X		
Water Authority	Evaluation of yields of reservoirs	X		
Water Authority	River regulation schemes	X (design)		X (operation)
Water Authority	Aquifer recharge calculation	X		
Water Authority	Leaching of waste tips	X	X	
Water Authority, Met. Office	Storm analysis	X	X	
Water Authority, Met. Office	Urban drainage design	X	X	
Water Authority	Flood forecasting/warning			X
Met. Office	Rainfall forecasting			X
Met. Office	Research and development	X	X	X
Met. Office	Soil moisture deficit maps	X		X
Met. Office	General enquiries	X	X	X
Met. Office	Climatic change	X		
Met. Office	Radar–rainfall research	X	X	X
MAFF*	Irrigation requirements	X		
MAFF	Field drainage design	X		
MAFF	Forecasts for crop diseases			X
MAFF	Crop development and husbandry studies	X		

* Ministry of Agriculture, Fisheries and Food.

that the known 'good' sites in the existing network should be retained in the new network, and that other sites should be improved.

(b) *Evaluation of the existing network*

(1) *Operational considerations.* It is necessary to classify the sites to identify those which it is desirable to retain in a redesigned network, and those which must be improved if they are to be included in the new network. The quality of the exposure of a site can be judged by inspection and the reliability of the observer and the observations can be evaluated by considering the numbers of apparent errors which are identified during the routine, computer-assisted quality control procedures over a period of time.

Using these assessments and other information, such as the length of record, a classification of a site can be made. As an example of this, Table II shows the classification of the sites in the Wessex Water Authority area, taken from O'Connell *et al.* (1978). Only those sites registered by the Meteorological Office in 1978, when the study took place, are included.

Table II. *Classification of registered rain-gauge sites in the Wessex Water Authority area in* 1978.

Classification	Number of sites: Daily	Monthly
Class A: should be retained	92	3
Class B: should be retained or removed	116	24
Class C: should be removed	23	4
Totals	231	31

(2) *Statistical methods.* Statistical methods for evaluating the performance of networks can be applied in two ways. Where a measured or estimated rainfall quantity forms the basis of some decision, this is deemed a direct use of rainfall data. Where rainfall data represent only one input to a decision-making process involving a number of variables, perhaps represented by a model, this is classified as an

indirect use. The corresponding statistical techniques, which can be referred to as direct and indirect methods, are described fully in O'Connell *et al.* (1977, 1978).

The direct methods of network evaluation used in this case involve the calculation of errors to be expected from optimal interpolation of gauged rainfall values to ungauged points or areas, followed by a comparison of these errors with those which are acceptable to users. As an example, optimal point interpolation errors for daily and monthly totals were estimated and mapped over the Wessex Water Authority area using the following procedure:

(i) Divide the region into a uniform square grid with elementary grid squares of side 5 km.

(ii) For each square of the grid:

(a) Obtain historical rainfall data for all gauges sited within a surrounding square of side 35 km centred on the given square.

(b) Calculate for this sample the correlations and variances of the rainfall data for pairs of stations lying within 35 km of each other.

(c) Fit a correlation function to the sample correlations and obtain an average variance for the region. This determines a fitted covariance function.

(d) Obtain the locations of gauges in the existing or proposed network which are within the outer square of side 35 km. Let this be the interpolation set for the given (5 km $\times$ 5 km) inner square.

(e) Using the gauges in the interpolation set, calculate the mean-square error of interpolation to each point on a 1 km square grid within the inner square.

(iii) The procedure is repeated for all 5 km $\times$ 5 km squares. The surrounding squares of size 35 km $\times$ 35 km used for adjacent 5 km $\times$ 5 km squares overlap each other to a considerable extent providing smoothing, firstly of the correlation parameters and secondly of the interpolation accuracy.

(iv) Using the 1 km grid values ((ii)(e) above) of point interpolation error, produce a contour map of the interpolation error for the whole region.

This technique is illustrated in Fig. 1.

Various categories of daily data can be analysed in order to show the differences in correlation structure (and the resulting effects on interpolation accuracy) between 'wet' days only, 'very wet' days only, or a mixture of 'dry' and 'wet' days chosen essentially at random. Monthly or annual correlation functions can also be calculated. Once correlation functions have been fitted for the chosen areas and categories of rainfall data, the estimation errors (expressed, for example, as root-mean-square errors) can be derived for optimal estimation procedures which use existing (or proposed) rain-gauge networks to interpolate to grid points, thus allowing maps of interpolation error to be drawn. Using the maps it is possible to identify the areas of deficient or superfluous accuracy with respect to the users' requirements. Similarly, the accuracy of areal estimates can be calculated and compared with the requirements of users. Examples of the use of these direct methods of network evaluation are given in a later section.

The use of indirect methods of network evaluation is limited by the difficulty of modelling some of the decision-making processes to which rainfall is an input. Two possible approaches would be (a) to study the effects of daily rain-gauge density on the accuracy of streamflow simulation using a daily rainfall run-off model and (b) to study the effects of telemetering gauge network density and configuration on the accuracy of short-term flow forecasts. Since, however, deterministic models of actual streamflow tend to give misleading results, their extension to provide guidance on the relative performance of redesigned rainfall networks does not entirely recommend itself and possible procedures will not be discussed further here.

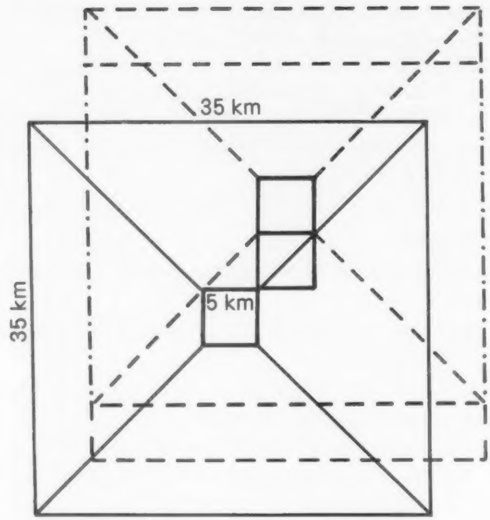

Figure 1. Square regions used for interpolating to points within each adjacent 5 km square.

(c) *Redesigning rain-gauge networks*

Having evaluated users' data requirements and the performance of the existing daily and monthly gauge networks, a set of design criteria can be determined for the rationalized networks. From a consideration of these criteria and by using a step-by-step design procedure the most appropriate distribution of rain-gauges within the network results. This procedure will include the use of the direct methods to evaluate the design network at various stages. By specifying alternative criteria, for example a different inter-gauge spacing, a selection of possible rationalized networks can be produced before the final choice is made.

The procedure used to redesign the Wessex Water Authority daily and monthly networks may be summarized in seven steps as follows:

Step 1. Set up a basic network with a chosen uniform gauge spacing, using existing registered or unregistered daily or monthly sites where possible, but otherwise specifying the locations of new gauges in centres of population only.

Step 2. Add any sites operated by or for the Meteorological Office but not included in Step 1, as these may be expected to continue to operate, irrespective of the rationalization exercise.

Step 3. Add any sites with records over a chosen length not included in Steps 1 or 2.

Step 4. Consider replacing any sites proposed in Step 1 by adjacent sites added in Steps 2 or 3.

Step 5. Add any remaining 'Class A' sites (see Table II), to provide as many reliable data as possible as a basis for the Meteorological Office computerized quality control routines, and to provide a measure of redundancy in the event of unexpected closures.

The network so far may be called a Preliminary Design Network.

Step 6. Evaluate this Preliminary Design Network in terms of its capacity to meet users' requirements by mapping point interpolation errors and calculating areal rainfall estimation errors. Adjust the density of gauges in the areas of deficient or superfluous accuracy.

Step 7. Repeat Step 6 until the desired level of accuracy is achieved in all important areas.

Three networks of daily and monthly gauges were designed for the Wessex Water Authority area using the step-by-step approach, each designed to meet different levels of users' requirements. The network adopted for implementation comprises 220 gauges compared with the existing networks of 333 daily (232 of them Meteorological Office registered) and an additional 46 monthly (30 registered) gauges. This network was designed to be at least as accurate on average as the existing networks and satisfied the design criteria of (a) a basic inter-gauge spacing of 10 km and (b) inclusion of all sites with a record length of at least 50 years. The evolution of this network is shown in Table III.

Table III. *Number of gauges added at each step of design procedure for the Wessex Water Authority Design Network.*

Step	Number of gauges added	Notes
1	133	Basic Network: gauge spacing approx. 10 km
2	13	Sites operated by or for the Meteorological Office
3	25	Criterion for record length: 50 years
4	−2	Two gauges replaced
5	12	Remaining 'Class A' sites
Preliminary Design Network total	181	
6	20	After comparison with users' requirements for data
7 (iteration)	19	
Design Network total	220	

A comparison of the accuracies of the existing and design networks in Table IV shows, for point interpolation, the percentage of the area which has a root-mean-square error of estimation less than specified values. These values were selected, depending on the category of data, so that the existing networks achieved these levels over some 90 per cent of the area. The four categories of data used were: (a) every fifth day's rainfall, irrespective of the amount, (b) days with an average areal rainfall greater than 1 mm, (c) days with an average areal rainfall greater than 5 mm, and (d) monthly rainfall. In the case of (b) and (c) a gap of five days was left after each day chosen, in order to minimize serial correlations between rainfall days.

Table IV. *Evaluation of network accuracy. Percentage of Wessex Water Authority area with root-mean-square errors of interpolation (RMSE) less than stated amounts.*

Network	Number of gauges	RMSE $\leqslant$1·0 mm every 5th day	RMSE $\leqslant$1·5 mm on days with areal rain $\geqslant$1 mm	RMSE $\leqslant$2·0 mm on days with areal rain $\geqslant$5 mm	RMSE $\leqslant$6·5 mm monthly totals
Existing daily	333	90·3%	88·2%	89·4%	
Existing monthly	379				92·9%
Design	220	91·0%	94·4%	90·6%	90·2%

Although a similar step-by-step method could be used to redesign recording-gauge networks, a shortage of recording-gauge data in computer format precluded the use of an objective method in this case, so a more empirical technique was used. Three recording-gauge networks were designed for the Wessex Water Authority area using, where possible, sites from the design daily networks which already have recording gauges. The users' requirements for recording-gauge data were considered at the design stage; for example, extra gauges were proposed in specified urban areas. The recording-gauge network which was adopted for implementation and which was intended to complement the design daily network of 220 gauges, comprised 77 gauges and had a basic inter-gauge spacing of 20 km.

A qualitative assessment of the benefits of rain-gauge network rationalization

The regional Water Authorities and the Meteorological Office, as major users of rainfall data, maintain the rain-gauge networks and collect, process and disseminate the data. Thus it is reasonable that all these organizations and also the customers of the Meteorological Office should be seen as the principal beneficiaries of a rationalization that leads to spatially uniform data of a higher standard, although from fewer gauges.

Whilst it is not a simple matter to quantify the real costs of running a rain-gauge network, or the savings to be made by rationalization, the reasonable expectation is that a reduction in the number of gauges will mean a reduction in operating costs. As regional Water Authorities carry the main burden of operating the networks, they see advantages in reducing the number of gauges. There is also a spin-off to the Meteorological Office which, apart from operating a number of gauges, also provides inspectors to ensure that sites and observational practices are maintained at a uniformly high national standard.

The major costs arising from data processing can be divided into two parts. These are, firstly those associated with the collection and initial visual checking of the data, which have costs proportional to the number of gauges, and secondly the computer-based quality control and archiving procedures which have a relatively stable cost, not significantly dependent on gauge numbers. Regional Water Authorities mostly undertake the first part and the Meteorological Office undertakes the second part. The evidence presented by O'Connell *et al.* (1978) is that the sophisticated but crucial quality control procedures are the most costly step in the data-gathering exercise.

The advantages of the rationalization of the Wessex Water Authority network (O'Connell *et al.* 1978) can be illustrated as follows:

(a) *Reduction in gauge numbers*

(1) From the Wessex Water Authority point of view:

—Before rationalization 333 daily and 46 monthly gauges (including 117 gauges not registered by the Meteorological Office).

—After rationalization 220 daily gauges (all of which would be registered).

—A net reduction of 42 per cent.

(2) From the Meteorological Office point of view (that is, considering only registered sites):

—Before rationalization 232 daily and 30 monthly gauges.

—After rationalization 220 daily gauges.

—A net reduction of 16 per cent.

The Wessex Water Authority clearly has the most to gain (in reduced running costs) from implementing the rationalized network. However, it should be pointed out that in order to achieve the more uniform reduced network, a number of new sites have had to be found and gauges installed, at some capital cost. Offsetting this is the improved standard of records provided by the new network. Such improvement also argues against the need to build significant station redundancy into the network.

(b) *Quality of the network*

All users should benefit from the Wessex design network of 220 gauges which, as well as achieving approximately the same general level of accuracy as the existing (larger) network, has other virtues. For example, the more uniform design network has a background inter-gauge spacing of 10 km (which helps to meet enquiries, particularly legal ones, for information at or near specific locations), all sites which have provided good quality data and those with very long records are included, and the sites which are maintained by or for the Meteorological Office are also retained. In addition, the rationalization exercise has highlighted shortcomings in the operation of some sites, which should be corrected before the sites are included in the design network. All of these features should encourage confidence in the data and allow better use to be made of them.

(c) *A demonstration of the advantages of the objectively based technique*

Fig. 2 shows for the Wessex Water Authority how the average level of accuracy of point estimation varies according to the number of gauges in the networks. This level of accuracy is expressed in terms of the percentage of the Wessex Water Authority area which has a root-mean-square error for point interpolation greater than 1·5 mm on days with an average rainfall over the area of 1 mm or more. The line marked 'Existing (or reduced) networks' demonstrates the effects of simple reductions in gauge densities. Apart from the points for all daily gauges (333) and all registered gauges (232), points are shown for one-half, one-quarter and one-eighth of all registered gauges, with each derivative being achieved by removing every second gauge from the previous network. The four points on the

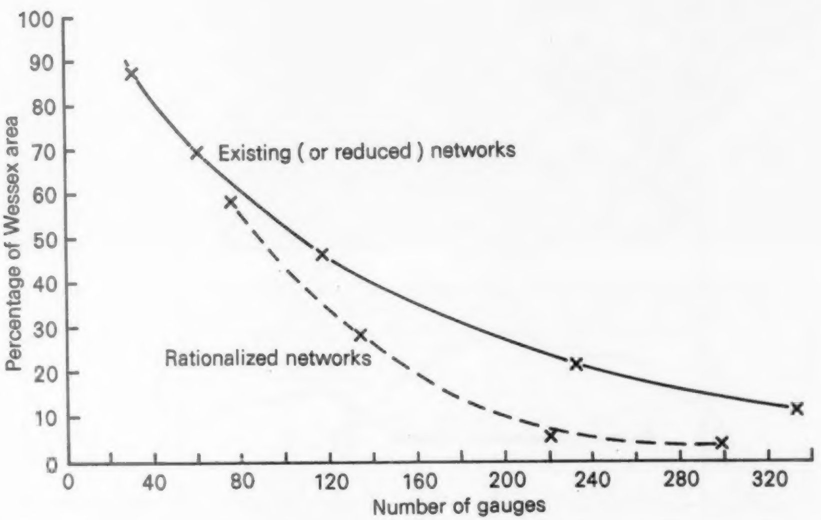

Figure 2. Percentage of the Wessex Water Authority area having a root-mean-square error of interpolation greater than 1·5 mm (for point interpolation on days with more than 1 mm of rainfall) for the different networks considered in this paper.

'Rationalized networks' line represent the networks designed for the Wessex Water Authority area:

75 gauges—that is, one gauge every 15 km
133 gauges—that is, one gauge every 10 km
220 gauges—that is, one gauge every 10 km, plus additions
297 gauges—that is, one gauge every 7 km, plus additions.

It can be seen that, for a given number of gauges, the rationalized networks always achieve a greater level of accuracy, and thus it follows that the rationalized networks require fewer gauges to achieve a chosen level of accuracy. For example, for a network of 200 gauges in the Wessex Water Authority area, a rationalized network would achieve the chosen level of accuracy (that is a root-mean-square error of interpolation less than 1·5 mm on days with average rainfall over 1 mm) over 90 per cent of the area, whilst a network derived by simple reductions of the existing network would achieve the chosen standard over only 67 per cent of the area.

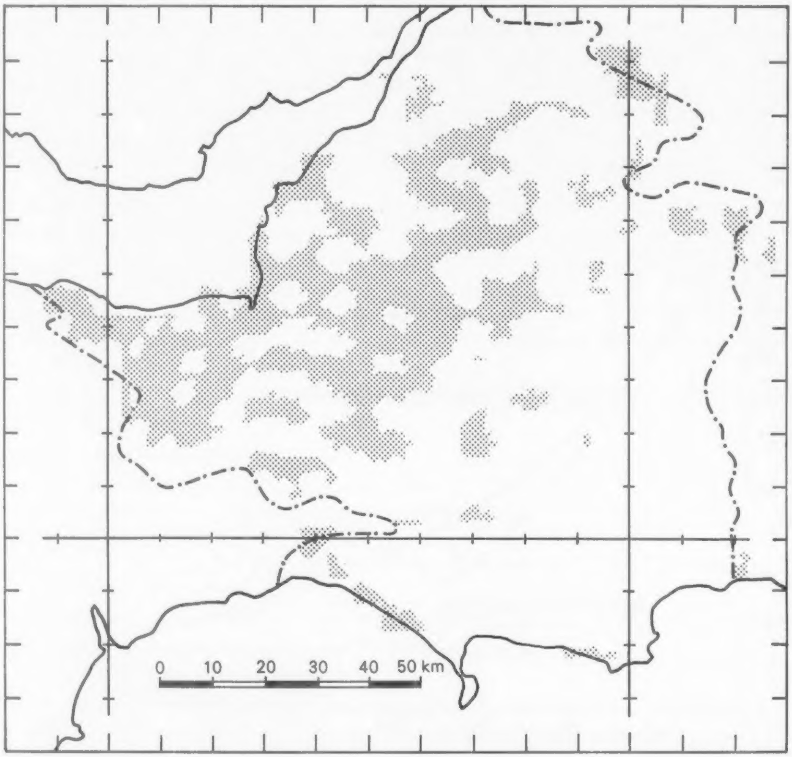

Figure 3. Regions (shaded) for which the root-mean-square error of optimal interpolation is greater than 1·5 mm for days with widespread rainfall of over 1 mm.
Basic Design Network of 133 gauges (one gauge every 10 km).
·—·— Wessex Water Authority area boundaries.

Plate I. L. G. Groves Memorial Prize and Award winners with Mr Nicholas Abbott and Air Marshal D. B. Craig. Left to right: Squadron Leader M. J. Bibby, Mr Nicholas Abbott, Air Marshal D. B. Craig, C.B., O.B.E., M.A., Mr T. Denholm, Dr P. J. Mason, and Flight Lieutenant J. G. Ticehurst. (See page 112.)

Plate II. Air Marshal D. B. Craig congratulates Flight Lieutenant J. G. Ticehurst, winner of the Aircraft Safety Prize.

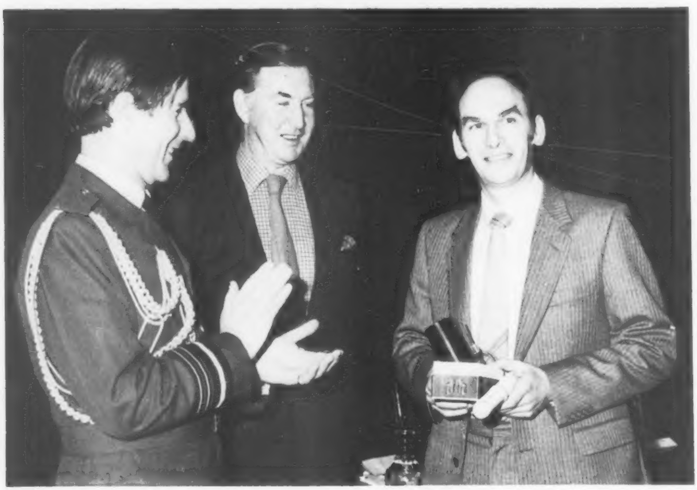

Plate III. Dr P. J. Mason, winner of the Meteorology Prize, being congratulated by Air Marshal D. B. Craig and Mr Nicholas Abbott.

Plate IV. Squadron Leader M. J. Bibby receiving the Meteorological Observer's Award.

Plate V. Congratulations to Mr T. Denholm after being presented with the Second Memorial Award.

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Plate VI. Photograph of an oil painting of the Director-General, Sir John Mason, by Roy Barley. The original portrait was presented to Sir John by his senior colleagues on 18 December 1979 to mark the conferment of his knighthood.

Fig. 3 shows the parts of the Wessex Water Authority area which have a root-mean-square error of point interpolation of over 1·5 mm on days with average rainfall of over 1 mm for the rationalized network of 133 gauges—that is, one gauge every 10 km. It is clear from this that, despite a uniform spacing, the accuracy of estimation is less in the west than in the east of the area, even though this is a region of relatively uniform topography. Fig. 4 shows how the final design network of 220 gauges has overcome this difficulty, thus demonstrating how the objective approach is superior to empirical procedures.

Conclusions

The rationalization exercise carried out in the Wessex Water Authority area has shown that it is possible to use the methods developed by O'Connell *et al.* (1977) to redesign rain-gauge networks so that the users' requirements for data are satisfied in a more cost-effective way that results in considerable advantages to the organizations which manage the networks and the data.

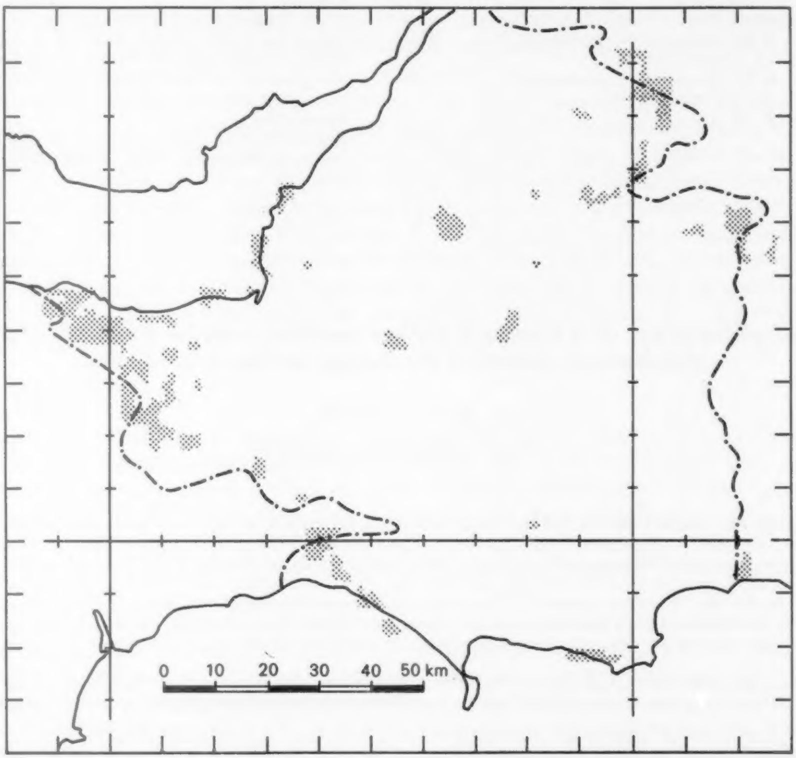

Figure 4. Regions (shaded) for which the root-mean-square error of optimal interpolation is greater than 1·5 mm for days with widespread rainfall of over 1 mm.
Final Design Network of 220 gauges.
·—·—· Wessex Water Authority area boundaries.

Work is continuing on the general application of the methods to other areas, including those with highly variable topography (and hence highly variable rainfall) and those which are covered by precipitation-measuring radar systems.

However, it will be necessary, if the full benefits of rain-gauge network rationalization are to be derived, to consider ways in which the collection, processing and dissemination of rainfall data can be made more efficient.

Acknowledgements

The Rain-gauge Network Rationalization Project described in this paper was a collaborative effort involving many people from the Institute of Hydrology, Wessex Water Authority, the Meteorological Office, and the Department of the Environment.

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The performance of a Campbell–Stokes sunshine recorder compared with a simultaneous record of the normal incidence irradiance

By H. E. Painter

(Meteorological Office, Bracknell)

Summary

The duration of bright sunshine has been evaluated from the record of normal incidence irradiance at Kew Observatory for specific thresholds of the irradiance. These durations are compared with the corresponding values obtained with a Campbell–Stokes sunshine recorder, using cards manufactured in the United Kingdom. The irradiance threshold to produce a burn on the sunshine recorder card varied from 106 to 285 W m^{-2} provided the sphere was unaffected by dew etc. The most important factor affecting the measurements of sunshine cards is the extension of the burn during intermittent strong sunshine; this can produce overestimations of sunshine durations for hourly or daily values of more than 100 per cent. The loss of record by the sunshine recorder due to dew, frost, etc. on the sphere is discussed.

Graphs are presented from which the monthly records of duration of sunshine at Kew could be corrected to a given threshold of irradiance, on the assumption that the experimental period is representative of previous years.

Introduction

For over a century the duration of bright sunshine has been recorded by comparatively simple devices. In many parts of the world the Campbell–Stokes recorder has been, and still remains, the instrument for such measurements. The principle of operation of this instrument is the production of a burn on a card

by the sun's rays brought to a focus on the card after passing through a glass sphere. Bright sunshine, as thus measured, is therefore the duration for which the normal incidence irradiance exceeds a threshold which will produce a discernible burn on the card. This threshold has not been precisely defined. The World Meteorological Organization in its *Guide to meteorological instrument and observing practices* (1971), section 9.10.1, suggests that the threshold can vary between 70 and 280 W m^{-2}. It is essential with such an instrument that the specification of its dimensions and of the composition of the glass sphere and the card are precisely defined in order to get comparability of results from different instruments.

The limitations of the Campbell–Stokes type of sunshine recorder are well known and have been discussed by Bider (1958). The two major problems are the variability of the threshold of irradiance to produce a burn and the overburning of the card in conditions of intermittent high irradiance. Bider (1958) showed that on average throughout the year the threshold for burning was about 8 per cent less at sunsets than at sunrises and attributed this fact to the card being more subject to dampness from dew in the early morning than in the evening. The problem of overburning is very difficult to evaluate; one small burst of high normal incidence irradiance causes a burn of duration far longer than the few seconds of its actual duration and rules have therefore been made to take account of this fact when measuring the lengths of burns.

Although the Campbell–Stokes sunshine recorder is an inexact instrument it has its advantages in that it can be used at isolated sites without an electrical power supply, is comparatively easy to maintain and use and is likely to be in service for a considerable time in the future. A demand has arisen for a sunshine recorder with an electronic output to be used on automatic weather stations. From a climatological viewpoint, a relationship would be required between any new type of sunshine recorder and the Campbell–Stokes sunshine recorder. With modern data logging methods and computer facilities it is now possible to investigate in more detail the performance of a sunshine recorder in relation to the record of normal incidence irradiance measured by a pyrheliometer. Such a comparison is here presented for the period from May 1979 to February 1980 from Kew Observatory, about 16 km west of central London.

Instrumentation

The sunshine recorder was the standard Meteorological Office instrument used for routine measurements, with cards manufactured in the United Kingdom. The cards were changed after sunset and measured in the approved manner. There is, of course, an element of subjectivity in measuring the burns on sunshine cards. The cards from Kew were measured by a number of different observers and each card was checked by a second observer; also random-check measurements were made by the Climatological Services Branch of the Meteorological Office to ensure that the national standard of measurement was being maintained.

The normal incidence pyrheliometer was the standard instrument which automatically tracks the sun. The solar alignment of the instrument was checked several times daily. The output from this instrument was punched on paper tape and also plotted by an analogue recorder. The analogue record was inspected and whenever it was defective because of instrumental failure (this includes the few occasions when the pyrheliometer was not correctly aligned) such records were deleted for this comparison. The normal incidence irradiance was sampled at one-minute intervals and thus there was not a continuous record of the irradiance and, therefore, on occasions of intermittent sunshine there could have been rapid changes between successive samplings. Hereafter the term irradiance is to be understood as referring to the normal incidence irradiance.

Analysis of the data

The irradiance data were formed into a continuous record by drawing straight lines between successive one-minute data. The durations, when the irradiance was above certain threshold values, were then evaluated. This was done for each hour of local apparent time corresponding to the times of the evaluations of the cards of the sunshine recorder. Durations were evaluated for each threshold of irradiance from 20 W m^{-2} by increments of 20 W m^{-2} up to 240 W m^{-2}. For each of these durations there was also given the number of times the irradiance record traversed the threshold value. These traverses could be either from below to above or from above to below the threshold. Hence, from the irradiance data were formed a series of durations of sunshine for each hour of each day for specified values of irradiance thresholds. The ratios of the monthly totals of these durations to the corresponding monthly durations from the sunshine recorder are shown in Fig. 1 for each month of the period under consideration. Each month comprised days of widely different sunshine conditions and another set of curves are shown in Fig. 2 for selected days as examples of particular conditions. The 14 May and 25 December were selected as days with continuous sunshine apart from a few breaks just after sunrise and just before sunset. The overburns on the cards for these days were likely to be minimal. The 17 January, 25 June and 14 August were examples of days with intermittent strong sunshine and any overburning of the records would be accentuated because of the numerous breaks in the sunshine. The 14 August was

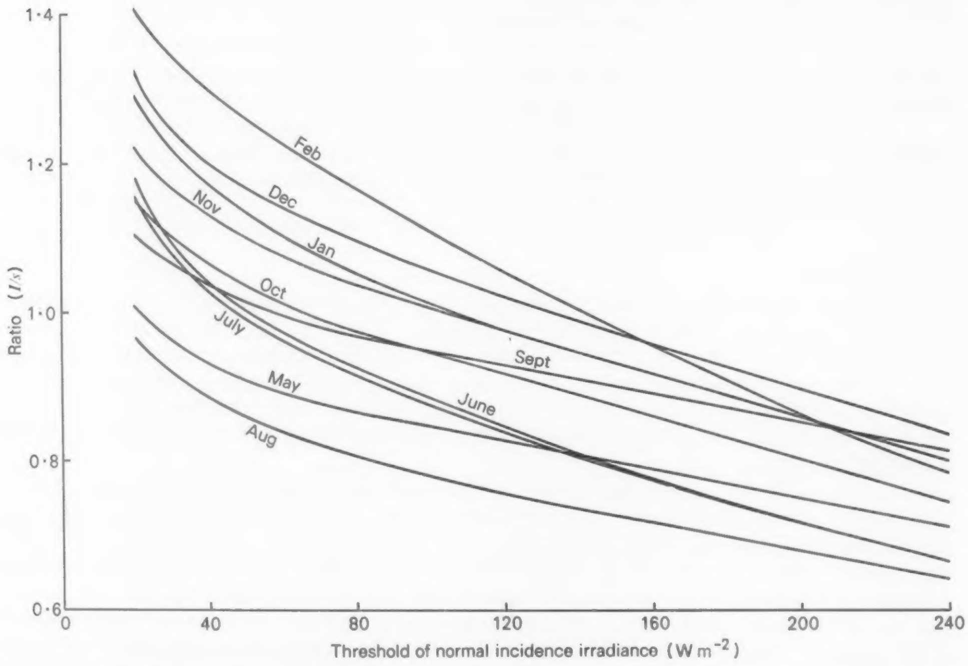

Figure 1. Ratios of monthly sunshine durations for various thresholds of normal incidence irradiance (I) to the corresponding values from the Campbell–Stokes sunshine recorder (s).

the day with the maximum number of traverses of the irradiance thresholds; for five hours there were over 20 traverses per hour. The 19 February was a hazy day with intermittent but not very strong sunshine.

The particular point of interest in Fig. 2 is the range in the threshold of equality between the two methods of evaluating the sunshine duration. In the case of the three days in which overburn is minimal the threshold of equality is about 130 W m^{-2} in summer and about 200 W m^{-2} in winter. (These thresholds are the average daily values; there are variations from these mean values at different times throughout each day.) The three days with strong intermittent sunshine have a threshold of equality of 45 W m^{-2} or less and there is obviously some other factor affecting the measurements of the burns on the sunshine cards which was not present in the previous cases. The implication from these curves is that if 130 W m^{-2} is the approximate threshold for burning in summer, then on 14 August the sunshine recorder measurement is overestimated by a factor of about 2·3.

A further analysis was made of all hours throughout the 10-month period when the sunshine recorder measured 0·9 hours of sunshine. Mean values of the corresponding durations from the irradiance data were evaluated for each of the irradiance thresholds used above and also for 1, 2–5, 6–10, 11–15, and more than 15 traverses of these thresholds. The results are shown in Fig. 3 where it is seen that, for a given threshold, the greater the number of traverses the smaller is the duration of sunshine evaluated

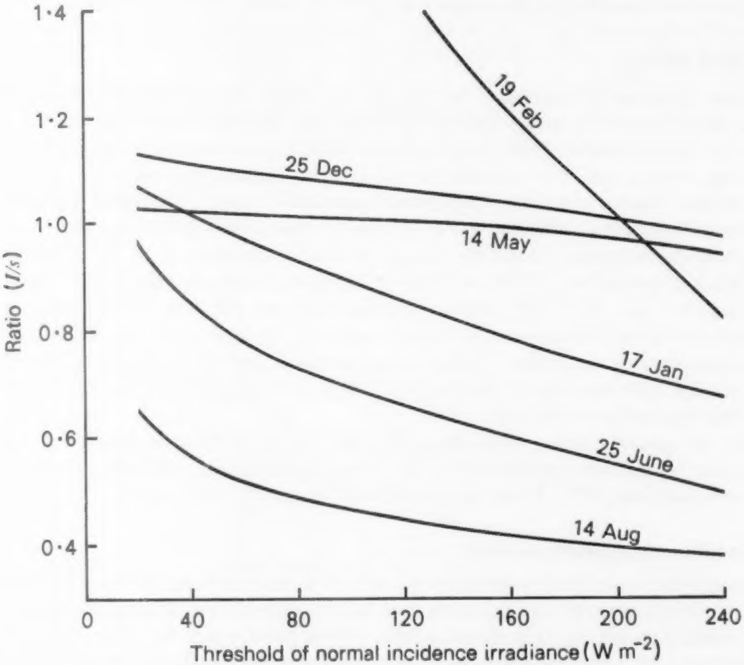

Figure 2. Ratios of sunshine durations for various thresholds of normal incidence irradiance (I) to the corresponding values from the Campbell–Stokes sunshine recorder (s) for particular days.

from the irradiance data. In the extreme case the 0·9 hours of the sunshine recorder is on average only 0·5 hours from the irradiance data. There can be little doubt that the increasing overestimation of the sunshine-card records with the increasing number of breaks in the record results from an extension of the burns, particularly with high irradiances.

From Fig. 1 it is seen that the curves show a marked seasonal effect. This arises firstly because the threshold of burning is higher in winter than in summer as a result of generally lower temperatures and damper conditions, and secondly because irradiances are generally lower in winter than in summer and therefore the overburn of the cards (and hence the overestimation of the measurements) will be less in winter than in summer.

In Figs 1 and 2 the threshold of equality, or in other words the effective threshold of the sunshine recorder, is the irradiance threshold necessary in order to equate daily or monthly sunshine durations produced by the two methods. From Fig. 1 it is seen that the effective threshold ranged from 142 W m^{-2} for February to about 16 W m^{-2} for August.

The monthly curves in Fig. 1 apply only to the period under consideration and are not necessarily representative of their respective months for other years. In order to arrive at more general mean curves the data for May to August, for September and October, and for November to February have been combined to give in Fig. 4 representations of the mean curves for summer, equinox and winter respectively. The slight difference in shape between the equinoctial curve and the other two curves is probably due to poor sampling for the equinoctial curve for which only two months' data were available.

The threshold of burning

The irradiance threshold of burning of the card of the sunshine recorder has been estimated from some of the data given above but actual measurements of this threshold were also made. As has been observed, for example by Bider (1958), the threshold of burning is on average higher in the early morning than in the late evening and so on all suitable occasions an examination was made of the commencement of burns after sunrise and of the cessation of burns before sunset. Examples were used only if the rate of change of irradiance with time was very small, so that errors of two minutes in estimating the time of the burn did not make a big difference to the irradiance value. Over the 10-month period the mean irradiance threshold was 193 W m^{-2} for 41 samples in early mornings and 154 W m^{-2} for 44 samples in late evenings. The lowest value of this threshold was 106 W m^{-2} in the evening on a day of almost continuous bright sunshine. The highest value of the threshold was 301 W m^{-2} on a hazy morning in September; it is possible that there may have been dew on the sunshine recorder sphere on this particular day. The next highest threshold of 285 W m^{-2} appears to be a genuine case of the card being wet after rain earlier in the night.

As a matter of general interest solar elevations were evaluated for a number of occasions of very early or very late burns on the sunshine card. There were six occasions with solar elevations of less than 3°, the lowest value being 2·3°. These low values were in summer and winter.

Loss of record from the sunshine recorder

The discussion above on the irradiance threshold was concerned only with the performance of the card of the sunshine recorder and assumed that the instrument, particularly the glass sphere, was otherwise in perfect condition. The measurements of threshold values, however, indicated that there were notable losses of record which must be attributed to dew or other water deposits on the glass sphere. There were three days on which the card did not produce a burn until the irradiance was greater than 400 W m^{-2}. If one assumes a mean threshold of burning of 200 W m^{-2} this implies a loss of

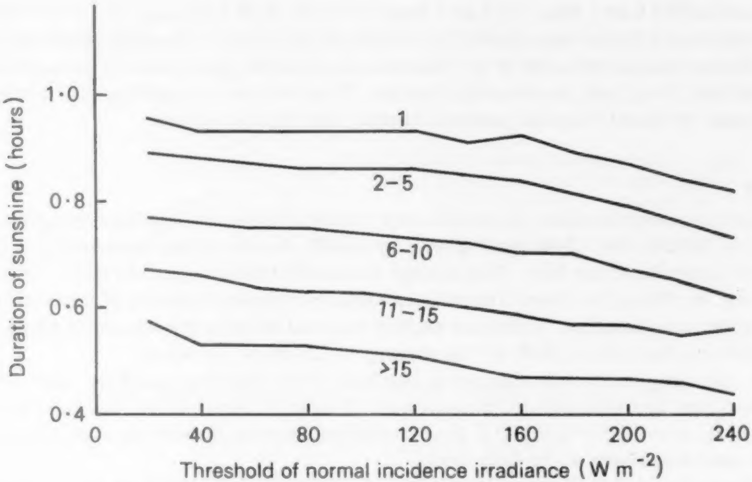

Figure 3. Mean durations of sunshine (hours) for various thresholds of normal incidence irradiance and for various frequencies of traverses of the threshold values on all occasions when the Campbell–Stokes sunshine recorder measured 0·9 hours.
Period: May 1979–February 1980.
The numbers of traverses of the thresholds are given against each curve.

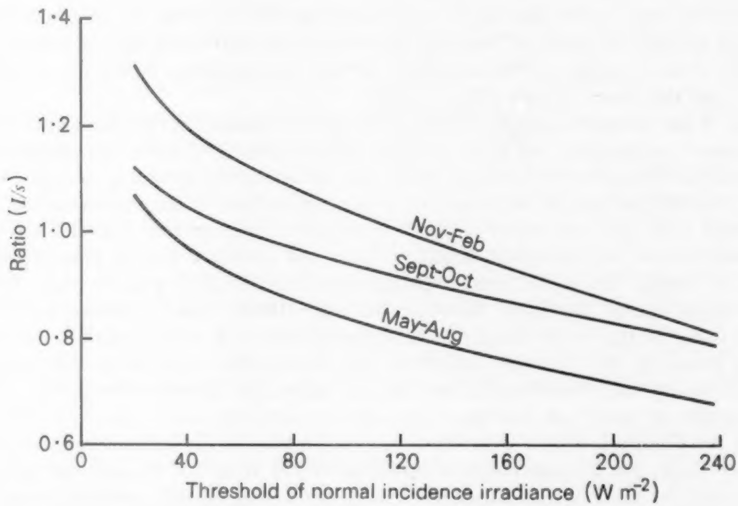

Figure 4. Ratios of sunshine durations for various thresholds of normal incidence irradiance (*I*) to the corresponding values from the Campbell–Stokes sunshine recorder (*s*) for various periods.

sunshine record of 0·8 h on 3 May, 1·2 h on 1 June and 0·7 h on 25 February. There were a number of days when there was a loss of record of 0·2 or 0·3 h from this cause. It seems probable that whenever the threshold of burning is above 300 W m^{-2} the transmission of the glass sphere of the sunshine recorder is reduced by dew, frost, rime, or even rain deposits. There was no very striking example in this comparison of losses of record from the sunshine recorder due to frost or rime.

Conclusions

The performance of the sunshine recorder is very variable because of the effect of weather conditions on the state of the card and of the glass sphere, but chiefly because of the overburning of the card in conditions of intermittent sunshine. The average measured irradiance threshold for a burn is about 170 W m^{-2} but the effect of overburn is to produce a mean threshold of equality of about 60 W m^{-2} over the period under consideration. There is a marked seasonal effect in this threshold which ranges for average conditions from about 30 W m^{-2} in summer to 120 W m^{-2} in winter.

Although rules are given to take account of overburn when measuring sunshine cards, nevertheless, on occasions of very broken sunshine a measurement of sunshine duration over an hourly period can be overestimated by over 100 per cent and if these conditions continue throughout a day there will be an error of the same magnitude in the daily total.

As the effective threshold will vary with weather conditions, daily values from the sunshine recorder must be treated with considerable reserve when used synoptically over an area or country.

It would be difficult, if not impossible, to construct another instrument that would reproduce the performance of the Campbell–Stokes sunshine recorder and, therefore, to obtain continuity of records using a new instrument it would be necessary to reduce archived monthly records of sunshine duration obtained from the sunshine recorder to a fixed threshold of irradiance by reference to curves of the type given in Fig. 4. There is therefore an urgent need for a scientific definition of bright sunshine.

The problem of frost on the glass sphere of the recorder will be greater at some stations, not only because of the greater prevalence of frost but also because the instrument may be visited only once a day when the card is changed. The instrument at Kew was inspected before the 06 and 09 GMT observations and the sphere cleaned when necessary.

The results of this comparison apply strictly to the weather conditions that prevailed at Kew during the period under consideration and when sunshine cards of United Kingdom manufacture are in use.

An unpublished comparison between the IRSR and the instrument system used in this trial showed the IRSR to record 6 per cent less sunshine over a two-year period. In the present trial the Campbell–Stokes recorder with UK cards recorded about 19 per cent more sunshine than did a pyrheliometer.

The specifications of the Campbell–Stokes recorder and cards are not, in practice, standardized throughout the world. The World Meteorological Organization (1971) paras 9.10.2.1 and 9.10.2.2)) recommended the Interim Reference Sunshine Recorder (IRSR) which complied with the detailed specification issued by the Meteorological Office together with cards which complied with the detailed specification issued by Météorologie Nationale. An unpublished report of a comparison between the IRSR system (i.e. with French cards) and the UK system (i.e. as used in the present trial) showed the IRSR system to record on average 6 per cent less sunshine over a two-year period. In the present trial the Campbell–Stokes instrument recorded about 19 per cent more sunshine than the pyrheliometer, using the average observed threshold of 170 W m^{-2}. To account for this 13 per cent discrepancy, the IRSR system must also over-register in intermittent sunshine (although perhaps to a lesser extent than the UK system) unless the burning threshold for the French cards is considerably lower than that for the UK cards.

Acknowledgements

I am indebted to Mr R. J. Armstrong for programming the data and to Mr F. Lumb for calculating the solar elevations.

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Noctilucent clouds over western Europe during 1980

By D. H. McIntosh and Mary Hallissey

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Table I summarizes the observations of noctilucent cloud (NLC) over western Europe during 1980 as reported to the Department of Meteorology, University of Edinburgh.

The times given in the second column of the Table do not necessarily indicate the duration of the display, though appearance and disappearance times are referred to in the Notes where known. In the third column brief notes of the displays enlarge on the facts listed in other columns—NLC forms discernible, tropospheric cloud conditions, photographs and sketches available. Co-ordinates of the observing stations and selected details of elevation and azimuth appear in the remaining columns.

Routine hourly observations were made at 15 meteorological stations in the United Kingdom, 4 in Sweden, and at Reykjavik in Iceland when darkness permitted. Observers at these stations provide information of sky conditions during all hours of darkness; the significance of 'negative' nights is obviously great when trying to assess the overall appearances of NLC.

Positive reports of the clouds were received for 32 nights during the 1980 observing season; this compares with 43 for 1979. Several observers have expressed the opinion that the clouds appeared less often and were not merely less often visible due to the prevalence of tropospheric cloud during the 1980 summer months. Mr Olesen of Denmark reported that, most unusually, he did not see a single appearance of NLC. Mr Parviainen's list of 9 displays visible at Turku, in Finland, makes a welcome contribution to the summary. His last sighting was on 7/8 August, and the last of the list was recorded by Mr Solås of Norway on 9/10 August—some weeks earlier than the end of the 1979 season. (An early sighting reported from Sundsvall for 6/7 April and a late one from Leuchars for 31 August/1 September are both treated as doubtful, as in each case the SDA (solar depression angle) is greater than 16°.)

Positive observations were received from 10 meteorological stations of the (hourly observing) group mentioned above, 5 from other British meteorological stations, from 3 Swedish stations, 1 Icelandic station, a Lufthansa pilot, and from voluntary observers in Dundee, Joppa (Edinburgh), Milngavie, Newton Stewart, Fiane and Turku. Points of observation of some displays were well scattered—on 2/3 July as far apart as Turku and mid-Atlantic.

Time-lapse photography was again carried out at the Department of Meteorology, Edinburgh, throughout the observing season, providing a record of nightly conditions there. The three clearest displays were on the nights of 21/22, 26/27 and 29/30 June. These two last dates and 13/14 July were the most widely reported displays of the season, but there was no outstandingly bright display. On 25/26 June a photograph of the display was taken at Machrihanish; on 29/30 June, 30 June/1 July and 31 July/1 August the displays were photographed at Milngavie, the last event, not because it was a striking display, but rather because the appearance was later in the season than Dr Simmons had previously recorded.

The help and co-operation of the many observers who were fortunate enough to see appearances of NLC and of the many more who watched in vain is gratefully acknowledged. A grant from the Meteorological Office makes possible the collection, collation and publication of the written and photographic data. All data so far have been incorporated by Dr Fast of the University of Tomsk into his catalogue of NLC data.

Table I. *Displays of noctilucent clouds over western Europe during* 1980

Date—Night of	Times UT	Notes	Station position*	Time UT	Max. elev. (degrees)	Limiting azimuths (degrees)
1980						
11/12 May	0243–0330+	Silvery-blue patches of NLC in zenith, medium brightness: tufted and striated formation. Possible W–E movement. Identification uncertain after 0330 in brightening sky. SDA approx. 10° (Sketch from Lyneham).	51·5°N 02°W	0300	90	—
13/14	0215	NLC suspected visible low on N horizon above distant hills from SW Scotland.	55°N 04·5°W	—	—	—
1/2 June	2400–0030	Suspected NLC veil visible Edinburgh with faint banded formation (time-lapse photo.).	56°N 03°W	—	—	—
5/6	2400, 0020	NLC veil with billow formation, medium brightness, visible Jönköping. Faded by 0045.	58°N 14°E	2400 0020	60 70	010–060 350–069
6/7	2200–2400+	Thin veil of NLC visible Leeming, hidden by tropospheric cloud before 0100.	54·5°N 01·5°W	2200 2300	5	360
11/12	0200	NLC suspected visible Tiree through cirrus. Nil visible at earlier observations of 2400, 0100.	56·5°N 07°W	—	—	—
15/16	2300	NLC visible N. Ireland. (Tropospheric cloud hampered visibility at 2200 and 2400.)	54·5°N 06°W	—	—	—
17/18	0030–0115 0200–0315	From Edinburgh, possible NLC behind tropospheric cloud. Completely obscured 0130.	56°N 03°W	—	—	—
19/20	0130–0300	NLC along N horizon visible Edinburgh through breaks in tropospheric cloud.	56°N 03°W	—	—	—
21/22	2400–0330	2 small patches of NLC visible Boulmer 2400, 0100. In Edinburgh NLC suspected visible between tropospheric clouds 0100, 0200. Clearance at 0215 showed parallel bands of NLC, medium brightness. Bands brightened against veil background at 0300. Faded into brightening sky at 0330.	56°N 03°W 55·5°N 01·5°W	0215 0315 2400 0100	10 — 4	020 020 030
24/25 June	2400–0230	At 2330 Benbecula noted clear sky and no NLC. At 2400 thin white veil of NLC visible, brightening slightly 0100, until fading into dawn light at 0230.	57·5°N 07·5°W	2400	5	330–010

* To nearest 0·5 degree.

Date—Night of	Times UT	Notes	Station position	Time UT	Max. elev. *degrees*	Limiting azimuths *degrees*
25/26	0100, 0200	Bright rippled bands of NLC visible N–NE at Tiree and Machrihanish; obscured by tropospheric cloud at Tiree at 0200, but still seen faintly farther south until fading into brightening sky.	56·5°N 07°W	0100	18	045
			55·5°N 05·5°W	0100	12	360–020
26/27	2130–0345	NLC became visible above tropospheric cloud to 16° elevation from SW Scotland. Bands of NLC to 7° visible NE England before midnight, rising to 10° with increasing brightness. At Joppa (Edinburgh) small patches visible 0035 to 15° elevation increased in brightness and elevation to 20°. Visible on film at Edinburgh from 0130—extensive display of bands and billows to high elevation by 0315; banded formation still visible faintly in NE at 0345. NLC visible at Tadcaster to 23° elevation around 0200, as 'flame-like' streaks. Most southerly point of recording, Marham (Norfolk) where highest elevation was at 0200–0225, when wispy patches reached 20°. Medium brightness reported generally.	56°N 03°W	0035	15	340–020
				0050	20	010
				0145	20	
				0245	30	360–045
				0315	30	360–040
			55·5°N 03°W	0100	12	320–030
			55·5°N 01·5°W	2345	7	360–020
				0045	10	350–030
			55°N 04·5°W	2215	16	360
			54°N 01°W	0200	23	360
			52·5°N 0·5°W	0148	10	340
				0200	20	340–020
				0225	20	340–020
29/30	2230–0315	NLC fleetingly visible at various points from Jönköping in E, across central and SW Scotland and N England; showing striated structure. From Edinburgh display visible for some 3 hours until fading into light sky at 0315 at high elevation. Band and billow formation clearly discernible for most of time, with densely packed NLC formation 0200 and 0215.	58°N 14°E	2350	50	360–050
			56°N 03°W	0020–0030	10	340–040
				0300	30	340–040
			56°N 04·5°W	2330	17	340–040
			55·5°N 04·5°W	0015	7	015–020
			55·5°N 01·5°W	0100	11	340–020
			55°N 04·5°W	2230		
30 June/1 July	2225–2301	NLC visible in W and SW Scotland for brief period, with streaks to fairly high elevation, joined by lateral wisps.	56°N 04·5°W	2230	21	045
			55°N 04·5°W	2230	16	360–040
1/2 July	2200, 0556	NLC seen at E and W extent of our coverage (Turku and Lufthansa aircraft): no details.	60°N 22°E	2200	—	—
			51°N 40°W	0556	—	—
3/4	2320–0015	Billow formation NLC remaining steady at high elevation reported from Visby; medium brightness fading to less bright, with slight extension of western edge during observation.	57·5°N 18·5°E	2320	30	020–030
				2350	30	010–030
				0015	30	350–030
4/5	2035, 2245	Faint display—no details—reported from Turku and Dundee.	60°N 22°E	2035	—	—
			56·5°N 03°W	2245	—	—
6/7	2400–0200	First visible Benbecula as thin veil of NLC above cirrus, with some brilliant white patches. At last observation visible showing brightly in gaps in tropospheric cloud.	57·5°N 07·5°W	2400	12	330–010
13/14	2100–0230	Uninterrupted viewing from several stations; fibrous and rippled formation, bright or brilliant at times, especially in NE quadrant: extensive azimuthal spread. Very detailed description of display as seen from Carlisle.	60°N 22°E	2100–2400	55	315–060
			57·5°N 07·5°W	2300	14	320–050
				0200		360–030
			55·5°N 04·5°W	0116		045
				0220		020–045
			55·5°N 01·5°W	2320	4	020–030
				0100	5	
				0200	11	010–035
			55°N 01·5°W	0040	8	010–035
			55°N 03°W	0045	8	350–020
				0100	8	360–020
				0130	9	
				0150	10	360–020
			55°N 04·5°W	0040		360–045
15/16	2145–2245	Lenticular patches and narrow bands of NLC visible Boulmer and, at same time, just faintly from Turku.	60°N 22°E	2230	15	???–025
			55·5°N 01·5°W	2200	9	350–010
				2245	7	340–020
18/19	2145–2300	Bright NLC visible—no other details.	60°N 22°E	2200	15	350–045
22/23	2215	Faint NLC visible Turku—no details.	60°N 22°E	2215	10	—
23/24	2120–2200	Small amount of NLC visible—medium bright—first at Turku and later at same latitude at Lerwick.	60°N 22°E	2130	—	—
	0050–0135		60°N 01°W	0100	10	360, 045
24/25	2110	Report of possible very weak NLC to zenith from Fiane.	59°N 09°E	2110	90	250
25/26	2120–2200	From Turku, at similar time as report of previous night from Fiane—faint NLC, but no further details.	60°N 22°E	2130	—	—
29/30	0400	Rippled formation NLC seen from Tiree in NE sector.	56·5°N 07°W	0400	10	040

Date— Night of	Times UT	Notes	Station position	Time UT	Max. elev. (degrees)	Limiting azimuths (degrees)
31 July/1 Aug.	2149–2345 0200	Earliest sighting 2149 at Joppa—very small faint patch of NLC, brightening 2210 into 3 bands. By now visible Milngavie, where veil and band structure visible for 30 minutes (SDA estimated 12°). Billowed formation bright at Benbecula 2300 to NW, seen as patch in NNW from Wick. Brightness also increased at Joppa as 3 bands merged into layer in NW. At 0200 NLC again visible from Wick in NNW.	58·5°N 03°W	2300	13	310–350
				0200	12	345
			57·5°N 07·5°W	2300	10	290–010
			56°N 04·5°W	2212	8	340–020
				2240	4	340–020
			56°N 03°W	2145	7	360
				2210	7	355–005
				2250	7	335–005
1/2 Aug.	2110	Spread of NLC to high elevation seen from Fiane.	59°N 09°E	2110	90	340
2/3	0030–0100	Bands of bright NLC visible Reykjavik to high elevation, visible until covered by altocumulus at 0100.	64°N 22°W	0030	25	—
7/8	2130	Very faint NLC visible—no further details.	60°N 22°E	2130	5	—
9/10	2110–2115	Diffuse veil of NLC to NE and E seen Fiane—possible banded formation.	59°N 09°E	2110	90	045, 090

Awards

L. G. Groves Memorial Prizes and Awards

The annual award of prizes took place on Friday 28 November 1980 at the Main Building, Ministry of Defence, Whitehall (see Plates I–V). Since the previous prize-giving Mrs Dorothy Groves had died, little more than a year after the death of her husband, Major K. G. Groves, so that all present felt strongly aware that for the first time both founders of this remarkable series of awards were no longer with us. The Vice Chief of the Air Staff, Air Marshal D. B. Craig, C.B., O.B.E., M.A., presided.

Air Marshal Craig opened the proceedings and referred to Mrs Dorothy Groves with warmth and respect. He then called on Mr Nicholas Abbott, as current representative of the Groves family, to present the prizes and congratulate the winners. Mr Abbott in his turn also referred to his great-aunt's death, and said that she had left a substantial legacy for the furtherance of the various prizes and awards. He welcomed in particular among those present who were members of or connected with Major Groves's family, Miss Patricia Halahan whose father, the late Air Vice Marshal F. C. Halahan, had joined the Royal Naval Air Service on its foundation by Churchill in 1914 together with Mr Abbott's grandfather, Robert Marsland Groves (Major Keith Groves's brother), having previously married one of the Groves sisters.

The 1980 Aircraft Safety Prize was awarded to Flight Lieutenant J. G. Ticehurst of Royal Air Force Coningsby for his proposals regarding the use of metal detectors for clearing air-to-ground ranges, with the following citation:

'During weapon training in the last four years, ricochet damage has been responsible for 10 RAF accidents classified Category 3 or worse, and 67 incidents where lesser degrees of damage occurred. The cost of the 10 accidents alone was just under £2·2 million. Although only one aircraft was destroyed, it is largely a matter of luck where the aircraft is struck by the debris and each impact could cause a major accident. Ricochet damage is caused by aerial-delivered weapons bouncing off the target structure, rocks or metallic debris in the ground from earlier weapon deliveries. To reduce this hazard, target structures are made suitably resilient and any rocks that can be found are removed

from the area. However, locating and removing buried metallic debris is more difficult and time-consuming. The method used on most air-to-ground ranges is to rake over the surface and dig up the debris that is revealed but this method is not one hundred per cent efficient and some debris will remain undetected. Flight Lieutenant Ticehurst researched this problem and discovered that a readily available and relatively cheap treasure hunters' metal detector would accurately pin-point buried metal in the immediate target area, where there is the greatest risk of a ricochet occurring. He therefore carried out an assessment to confirm the detector's suitability for the task. As a result, Flight Lieutenant Ticehurst has recommended that range personnel should be equipped with light-weight and inexpensive metal detectors to ensure more efficient removal of metal debris from our air-to-ground ranges, thus reducing the amount of costly ricochet damage.'

The 1980 Meteorology Prize was awarded to Dr P. J. Mason of the Boundary Layer Branch of the Meteorological Office for his work on airflow over hilly country and the numerical simulation of atmospheric boundary layers, with the following citation:

'Dr Mason has modelled various aspects of flow over hills, advancing our appreciation of the physical processes involved and significantly improving our ability to forecast the effects of hills and valleys on airflow. In support of this theoretical work he and his collaborators have organized several field experiments designed to measure the airflow characteristics over actual hills, seeking thereby to test the results of his computations. Recently he has capitalized on this work by developing a very elegant technique for representing roll vortices over flat terrain.'

The 1980 Meteorological Observer's Award was awarded to Squadron Leader M. J. Bibby, now serving at Royal Air Force Upavon, with the following citation:

'Squadron Leader Bibby joined the Meteorological Research Flight (MRF) as Officer Commanding the RAF unit in the summer of 1977 and was posted out three years later. During this time he quickly established his competence in the role of Officer Commanding MRF and also participated fully in the interpretation of the scientific objectives as far as the flying was concerned. His drive and enthusiasm proved his leadership qualities in the air and on the ground, not only to the other RAF crew members but also to the civilian scientists. In particular should be mentioned his contribution to the Joint Air–Sea Interaction (JASIN) project held in 1978 where, despite early difficulties due to poor weather and aircraft unserviceability, the whole of the flying contribution to the project was nevertheless achieved, largely by Squadron Leader Bibby's efforts and dedication.'

The 1980 Second Memorial Award was awarded to Mr T. Denholm of the Meteorological Office, with the following citation:

'The development of North Sea oil resources has required accurate weather forecasting services which are dependent *inter alia* on reliable observations from the offshore installations. Mr T. Denholm has served for the past four years as the first meteorological adviser to the offshore operators based at Aberdeen. During this time he has made over 100 visits to platforms and rigs both in the North Sea and to the west of Shetland, often in very adverse weather conditions, in order to advise and train oil company observers on the required procedures and associated instrumentation work. The observations so obtained have been especially important to helicopter flight safety. His zeal and initiative have undoubtedly improved observing standards in this area and have thus contributed towards a better weather service for operators working in a particularly hazardous environment.'

Review

Environmental instrumentation, by L. J. Fritschen and L. W. Gay. 240 mm × 160 mm, pp. xvi + 216, *illus*. Springer-Verlag, New York, Heidelberg, Berlin, 1979. Price DM 42, US $23.60.

The authors of this book intended it to be used as a text for advanced students and a manual for researchers studying the relations linking biological responses to atmospheric variables. A meteorologist will find the balance of the book rather unfamiliar, as certain topics receive an unusually detailed treatment, whereas others are discussed rather too briefly. However, the book includes descriptions of most of the types of instrument currently in use for near-surface meteorological measurements, and the authors give due emphasis to explaining the physical principles of operation of each device including the potential sources of errors, so the meteorologist too will find this book useful.

The first two chapters are entitled 'Measurement fundamentals' and 'Review of physical fundamentals', and are probably the least satisfactory chapters in the book. In Chapter 1 the sections on measurement errors and error estimation are too short to be of much use to anyone unfamiliar with these topics, and that person would benefit more by being referred to one of the standard texts. The introduction to the book states that the user is expected to have a basic physics and mathematics background and would therefore be familiar with most of Chapter 2, especially with such basics as Ohm's law or the formula for conduction of heat in a solid bar.

The most useful part of the book is made up of Chapters 3 to 8, which describe methods and devices for measuring temperature, soil heat flux, radiation, humidity and moisture, wind speed and direction, and pressure. Each chapter begins with a section which outlines some of the basic physics and mathematics involved in each type of measurement and the following sections describe types of sensors, usually with some guide to their suitability for a particular application and how to minimize errors. The examples of actual devices are chiefly of American origin, but at the end of each chapter the bibliography and list of literature cited include copious references from all parts of the world. Some of these references might appear rather old but, as the authors point out in the introduction, environmental instrumentation has not been drastically changed by recent technological developments and most of the advances have been in the methods of data recording and handling. These chapters, therefore, augmented by their references, provide a good review of current instrumentation, although the space devoted to each topic is not necessarily commensurate with its true importance. For example, the section on thermo-couples, with 16 out of 48 pages, takes up too much of the temperature chapter, and the chapter on pressure is far too short so that many modern types of transducer have not been mentioned.

The final chapter, 'Data acquisition systems', attempts too large a task in dealing with this vast and rapidly developing subject in only 16 pages. Much useful information is presented in this chapter, but anyone unfamiliar with the subject will probably be more confused than enlightened and sometimes the authors also seem confused.

The book is well printed and illustrated, with clear diagrams and excellent photographs of sensors. There are many useful tables which help to make it complete as a work of reference and there are few obvious misprints, although the section on radiation errors of thermometers is a notable exception since it contains several mistakes in equations which make them useless for calculating the magnitude of these errors.

This book satisfies many of the requirements of a reference manual of instrumentation. It may not provide the newcomer to the field with all the information required to solve a particular problem, but the reader should have gained sufficient knowledge to enable him to define the problem and evaluate a solution provided by experts or in a more complete text.

K. L. Webber

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NOTICES

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